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Same or different? Insights on public perception and acceptance of carbon capture and storage or utilization in Germany

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ABSTRACT

Carbon Capture and Storage (CCS) and Carbon Capture and Utilization (CCU) are two CO_2-based technologies aiming at mitigating climate change by capturing and either permanently storing CO_2 (CCS) or using it as a feedstock (CCU) for commercial products, e.g., chemicals, fuels, or plastic products. Whereas the implementation of CCS has attracted considerable public opposition in Europe and the US, the CCU-technology is still in an early development stage. This research takes a social science perspective and investigates the awareness, general perception and acceptance of CCS in comparison to CCU by applying an online survey in Germany (2017, n = 509). In addition, the risk perception of single steps in the CCU/CCS process chains was explored (CCS: CO_2-capturing, CO_2-transport, CO_2-storage; CCU: CO_2-capturing, CO_2-transport, temporary CO_2-storage, production, product usage, product disposal). Significant differences were found for the perception and acceptance of CCS and CCU: while both technologies were generally accepted, CCU was perceived significantly more positively than CCS. CCS-acceptance was negatively influenced by storage and transport risks; for CCU, disposal and product risks decreased acceptance. Our results contribute to the development of communication concepts for a successful implementation of CO_2-based technologies by considering public concerns.

1. Introduction

Today, worldwide efforts are taken to reduce greenhouse gas emissions to combat climate change (UNEP, 2017). A wide variety of innovative technologies are available that aim at reducing the production of greenhouse gases such as renewable energies for electricity production (IPCC, 2011) or the use of waste heat (e.g., Chen et al., 2010). A further approach to reduce carbon dioxide (CO_2) emissions is carbon capture, where CO_2 is still produced but only a small amount (< 10%) is released into the atmosphere. The captured CO_2 can be stored (Carbon Capture and Storage, CCS) or used as a feedstock (Carbon Capture and Utilization, CCU) (Markewitz et al., 2012).

Apart from the potential of CCS and CCU as parts of a strategy for climate change mitigation, the public perception of both technologies is a crucial factor for their successful deployment. People express concerns about health and environmental issues due to the perceived "toxic nature" of CO_2 (van Heek et al., 2017a). In the case of CCS, missing acceptance led to opposition and, especially in Germany, massive protests (Fischedick et al., 2009). Since CCU is also based on CO_2, which is converted into commercial products, it is important to understand how the public perceives CCU in contrast to CCS. This knowledge is highly valuable to support technical developers, policy, and industry in making decisions in line with public acceptance.

The present paper therefore focuses on comparing CCS and CCU regarding acceptance, perceived benefits and barriers as well as perceived risks concerning their technology process-chain. First, CCS and CCU are described, followed by the relevance of acceptance in technology development and empirical findings for CCS- and CCU-acceptance. Then, the study's methodological approach is described, and results are presented and discussed. Finally, recommendations are derived for technology development and communication concepts.

1.1. CO_2-based technologies

Fighting climate change by reducing greenhouse gas emissions is one of the most challenging tasks for industrialized countries (UNEP,

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2017). CCS has been intensively discussed as one measure to reduce CO_2 emissions into the atmosphere (Boot-Handford et al., 2014). In CCS, CO_2 typically emitted from large-scale sources is captured, transported to a storage location, and then permanently stored in the underground such as depleted oil and gas fields (Metz et al., 2005). According to scenarios for climate change mitigation, CCS could considerably contribute to achieving the 2 °C-target by reducing CO_2 emissions up to 25% until 2100 (IPCC, 2014). However, a successful business model for CCS-investment as well as economic incentives to support the high capital and operating costs of the entire CCS-process have not been developed yet (Leung et al., 2014). Hence, the pace of successful CCS-implementation worldwide is very slow and its effect as climate mitigation measure is still mostly theoretical (Bruhn et al., 2016).

Another CO_2-based technology, which has received increasing attention, is Carbon Capture and Utilization (CCU). CCU comprises a set of technologies, where CO_2 is captured from point sources or air and converted to be used as feedstock to produce plastic, chemicals, construction materials, or fuels (Markewitz et al., 2012). While the total amount of CO_2 potentially used for chemicals is small compared to global emissions (Bhave et al., 2017), CCU offers advantages beyond the CO_2-reduction potential. In particular, CCU can reduce the dependency on fossil resources (Artz et al., 2018). For example, crude oil can be partially substituted in the production process by using CO_2 as feedstock to produce polyols (Langanke et al., 2014), an intermediate product needed to manufacture plastic products, e.g., foam-mattresses (Covestro, 2015). This way, a reduction of fossil resources by 13 − 16% and of greenhouse gas emissions by 11 − 19% is possible compared to conventional polyol production (von der Assen and Bardow, 2014). Moreover, CCU could lead to the development of value-added chemical or biological products and, thereby, create new jobs (Styring et al., 2011).

CCS and CCU distinctly differ regarding their CO_2 reduction potential, the underlying technical processes and outcomes, their effects on climate mitigation, and their environmental policy targets (Bruhn et al., 2016). However, both technical concepts are often commingled in the public discourse, which might lead to biased perceptions of CCS and CCU by the public. This is especially relevant, as CCS projects have attracted considerable local opposition, which sometimes led to the cancellation of storage projects (Brunsting et al., 2011; L'Orange Seigo et al., 2014). Due to the similarity in naming and the low public knowledge about CO_2-based technologies (L'Orange Seigo et al., 2014; Perdan et al., 2017a), assumptions derived from CCS might be transferred to CCU and affect its perceptions and acceptance. Therefore, the present paper aims for a comparative analysis of CCS and CCU perceptions and acceptance. A focus was on perceptions of the technology process-chain, since both CCS and CCU have some process-chain steps in common (CO_2-capturing and -transport) but differ in other parts (storage site vs. production facility or in case of CCU: product usage and disposal). The environmental impact of single steps of the technology process-chain has been analyzed by life cycle assessments (von der Assen et al., 2013), however, perceptions of steps in the process chain and their impact on general acceptance have not been integrated into assessments of public perceptions and acceptance. The only study we identified in this context, focused on perceptions of CCS-technology-scenario design (Duetschke et al., 2014), not covering CCU-technologies. The knowledge about acceptance-relevant "hot spots" in the technology process-chain will provide knowledge for decision-makers and industry to develop and invest in acceptable CCU-technology-scenarios.

1.2. Public perception and acceptance of CCS and CCU

Today, most CCU-technologies are at an early development stage, but there are already some well-established CO_2-utilization pathways (most importantly: urea production). This means that the industrial roll-out of the CCU-technology and of CO_2-derived products has already begun (Covestro, 2016). However, an important prerequisite for the successful rollout of CCU is not only its technical and economic feasibility but also its public perception and acceptance. The public reaction towards a technology can put enormous pressure on policy and industry and influence or even stop further development and roll-out (e.g., protests against nuclear energy (De Groot et al., 2013) or fracking (Boudet et al., 2014)).

The perception of a technology refers to all kinds of perceived benefits, barriers, or risks associated with a specific technology. Technology acceptance denotes a positive attitude (approval) or supporting behavior (e.g., proclaiming, purchase, usage) (Huijts et al., 2012). The opposite dimension is active rejection (e.g. protests, lawsuits, consumer boycott). Apart from this active demonstration of (non)-acceptance, individuals can also adopt an indifferent position, where no attitude has been developed yet, or a passively suffering position (Schweizer-Ries, 2008).

The majority of studies on perceptions and acceptance of CO_2-based technologies investigated CCS-acceptance, which was found to be neutral to slightly positive with a rather low CCS-awareness (L'Orange Seigo et al., 2014). However, the neutral attitude towards CCS turns into rejection, when people are personally affected, e.g., by living close to a (planned) CO_2-storage location or a CO_2-pipeline. Being personally affected by CCS evokes higher risk perceptions, which are mainly based on health concerns about CO_2-leakage. This phenomenon is known as NIMBY-effect (Not in my backyard), which is not CCS-specific but also applies to the rejection of other infrastructural technology projects (Devine-Wright, 2013). Aside from perceived risks, benefit perceptions were identified as key factor influencing CCS-acceptance (Tokushige et al., 2007), whereas higher risk perceptions reduced CCS-acceptance (Yang et al., 2016). Perceptions of risks and benefits are also impacted by knowledge (Wallquist et al., 2010): higher knowledge about CCS and CO_2 was related to lower risk perceptions, while knowledge about CO_2-storage mechanisms increased perceived benefits and decreased risk perceptions. A higher climate change awareness also increased CCS-benefit perceptions.

For the acceptance of CCU, there is no comparable knowledge base available yet. Due to the early stage of implementation, first studies on CCU qualitatively explored laypeople's awareness, perceptions and acceptance-relevant parameters (Arning et al., 2017; Jones et al., 2014; Jones, 2015; van Heek et al., 2017a). These studies revealed a low CCU-awareness level. Environmental benefits (CO_2-reductions and fossil resource savings) were acknowledged, but there was also skepticism regarding the effectiveness of CCU as long-term solution for mitigating climate change. Risk perceptions were also prevalent, reaching from health concerns related to CCU-product usage (e.g., fear of allergies or suffocation from leaking CO_2) to environmental concerns (e.g., release of toxic substances during production) and product quality concerns (e.g., durability of products made of CO_2).

First large-scale online surveys on CCU-perception and acceptance followed just recently. These studies predominantly focused on CCU-product-acceptance, investigating the relationship between CCU risk perception and the acceptance of a CO_2-derived foam-mattress (Arning et al., 2017), segmenting acceptance-profiles for a foam-mattress as product example (Arning et al., 2018), and assessing preferences for an acceptable CCU-product-scenario (van Heek et al., 2017b). In summary, CCU-awareness and technical knowledge were found to be low, but the general perception of CCU was positive, despite concerns about health and product quality. The relevance of CCU-awareness was also emphasized by the findings of a recent survey on the perception of the CCU-technology (Perdan et al., 2017a). However, low levels of awareness and knowledge, as well as misconceptions about the underlying principles and risks of a technology can lead to wrong assumptions about another, only partly comparable technology. Upham and Roberts (2011) showed that laypeople use radioactive waste- and natural gas-storage as a frame of reference for CCS. In citizen panels on the

perception of hydrogen energy, several participants expressed associations with hydrogen bombs (Flynn et al. (2012). Since CCU is relatively unknown to the public, the evaluation of CCU might be framed by CCS perceptions. At the same time, no quantitative study systematically analyzed the perception of the technology process-chains of CCU and CCS so far. Therefore, the following research aims were pursued:

1 An assessment of public awareness, perception, and acceptance of CCS and CCU in Germany
2 A comparison of public awareness, perception, and acceptance of CCS and CCU
3 A comparison of (risk) perceptions of the technology process-chains of CCS and CCU

2. Methodology

The study's empirical approach is presented, starting with a detailed description of the questionnaire. Afterwards, the sample and the statistical analysis procedures are outlined.

2.1. Questionnaire

Questionnaire items were developed based on findings of qualitative pre-studies (Arning et al., 2017; van Heek et al., 2017a), where lay-people and experts were interviewed regarding CCS and CCU perceptions and acceptance. Before running the survey, the questionnaire was checked for comprehensibility, length of interview and wording. It was run as an online-survey, allowing a representative and efficient data assessment, using the service of a market research company to obtain a census-representative sample (regarding gender, age, and education) from all regions of Germany. Completing the questionnaire took, on average, 15 min. To assure measurement quality of the assessed constructs (internal consistency indicated by Cronbach's alpha), an item analysis was conducted (McDonald, 2013). All items of the survey, with respective descriptive statistics, can be found in Appendix B. The original German version of the questionnaire can be found in Appendix C.

The first part of the questionnaire assessed *demographic characteristics* (age, gender, education, zip code for the place of residence, residential area). The second part focused on *attitudinal variables*, such as attitude towards risks and safety, perceived CCS- and CCU-information level, environmentally conscious behavior, technical self-efficacy, and personal innovativeness. The *individual attitude towards risk and safety* was based on four items taken from the risk orientation questionnaire (Rohrmann, 2005), which evaluates the general tendency to take or avoid risks. The *perceived information level about the CCS- and CCU-technology process-chain steps* was assessed by asking the participants how well-informed they felt about CCS and CCU and the respective process-chain steps. *Environmentally conscious behavior* was evaluated by using four items, taken from studies on environmental awareness (Wingerter, 2014; Schahn et al., 1999). Here, the item number and content were reduced and adapted to the specific research context. *Technical self-efficacy*, i.e., an individual's confidence to use technical devices, was measured by using four items from the technical self-efficacy scale (Beier, 1999). *Personal innovativeness regarding technologies,* i.e., the perceived attractiveness of and interest in innovative technologies was assessed by four items (Fazel, 2014).

The third part of the questionnaire dealt with an *evaluation of the CCS- and CCU-technology*. To avoid sequence effects, the sequence of the two evaluation blocks (CCS and CCU) was randomized as well as the order of items within the evaluation blocks.

Each technology evaluation block started with a detailed introduction of the technology itself and the respective process-steps (CCS: capture, transport, storage; CCU: capture, transport, temporary storage, production, consumer product, disposal of products) (see Appendix A). Since the low public awareness makes it difficult to assess stable and valid perceptions of the CCS- and CCU-technologies (Best-Waldhober et al., 2006; Jones et al., 2015), a special focus was directed on the development of instructional material in the survey. It was important to achieve a basic understanding of the aims, application areas, and technology process-steps of CCS and CCU for the subsequent evaluations asked from the respondents. Therefore, the instructions were developed in cooperation with technical experts to ensure technical correctness. They consisted of a general introduction at the beginning of the questionnaire as well as CCU- and CCS-specific instructions displayed at the beginning of the technology evaluation blocks. The instruction text was formulated in a neutral way and contained factual knowledge about the CCS and CCU technology. It did not address potential risks and benefits of CCS and CCU to avoid biases in the subsequent evaluation of both technologies. In order not to overload respondents with complicated technical text, key concepts were illustrated by designers and the comprehensibility and clarity of the illustrations was tested.

In the CCS-technology evaluation block, respondents initially indicated their *local acceptance*, *i.e., attitude towards the construction of a CCS plant*, followed by an evaluation of *CCS benefits* (environmental relief and climate change mitigation). In a next step, respondents assessed potential *CCS barriers* (health and environmental risks, sustainability concerns), followed by a specific evaluation of perceived risks referring to the different process-chain steps of CCS-technology: *risks of CO_2-capture*, *risks of CO_2-transport*, and *risks of CO_2-storage*. Finally, participants assessed their general *acceptance of CCS*.

The CCU-technology evaluation block was structured identically. Respondents first indicated their *local acceptance,* followed by an assessment of *CCU benefits* (environmental relief, climate change mitigation, reduction of fossil resource consumption and dependency on their prices, and sustainable production). In the following, respondents assessed *CCU barriers* (health and environmental risks, sustainability concerns). Afterwards, perceived risks regarding CCU-technology process-steps were rated: *risks of CO_2-capture*, *risks of CO_2-transport*, *risks of a temporary storage of CO_2*, *risks during the production*, *risks of using CO_2-derived products*, and *risks concerning the disposal of CO_2 derived products*. Finally, the participants assessed their general *acceptance of CCU*.

All items were evaluated on six-point Likert scales. The scale granularity of a six-point scale allows a higher sensitivity of measurement, reliability, validity and discriminating power (e.g., Preston and Colman, 2000). The Likert scales were presented in combination with a verbal label, which supported the distinctness of the six scale levels (for most items: 1 = “I totally disagree”; 2 = “I disagree”; 3 = “I rather disagree”; 4 = “I rather agree”, 5 = “I agree” 6 = “I totally agree”).

Note that not all findings of the questionnaire are reported here due to space restrictions but will be presented in forthcoming papers.

2.2. Sample

The survey was conducted in Germany in January and February 2017. Survey data was collected by a market research company. Participants were part of on online panel and were paid for participating by the market research institute. During data-collection, we applied data-cleaning procedures (e.g., Meade and Craig, 2012) to control for data validity. All incoming data-sets were filtered according to a) completeness of responses, b) speeding (all respondents, which were faster than 35% of the median (7 min) were excluded) and c) for data quality based on consistency checks in respondents’ answering behavior. All respondents, which gave two or more inconsistent answers on predefined item pairs, which had the same content, but were positively and negatively poled (e.g. "I find CCU acceptable" . "I find CCU not acceptable") were excluded. From the total data set (n = 854), 40% of respondents (n = 345) were removed due to bad data quality. Information about bad quality data-sets was returned to the market research company and the recruitment of respondents continued until the predefined sample size was reached fulfilling quota- and data quality requirements. This way, only validated data sets (n = 509) were

Table 1
Demographic characteristics of the sample (n = 509).

Demographic characteristics		Percentage
Gender	Male	48.5%
	Female	51.5%
Age	Young (25–35 years)	17.5%
	Middle (36–55 years)	47.7%
	Old (56–75 years)	34.8%
Education level	No certificate (so far)	0.4%
	Basic school qualification	11.4%
	Secondary school certificate	23.0%
	Completed apprenticeship	26.7%
	Qualification for university entrance	13.4%
	University degree	23.0%
	Doctor's degree	1.8%
Region	Northern Germany (Bremen, Hamburg, Lower Saxony, Mecklenburg-Western Pomerania, Schleswig-Holstein)	20.2%
	Western Germany (North Rhine-Westphalia, Rhineland-Palatinate, Saarland)	26.5%
	Eastern Germany (Berlin, Brandenburg, Saxony, Saxony-Anhalt)	16.9%
	Central Germany (Hesse, Thuringia)	10.0%
	Southern Germany (Baden-Württemberg, Bavaria)	26.4%
Area of living	Urban	32.2%
	Suburban	43.2%
	Rural	24.6%

used for further analysis.

Gender was almost equally represented (48.5% male, 51.5% female). The age range was from 24 to 80 years and the mean age was M = 50.1 (SD = 12.4). Respondents had different education levels and came from all regions in Germany. According to quota setting in the data collection process, the sample was approximately representative for the German population in terms of age, region, education, and region (Table 1).

2.3. Data analysis

All constructs which were measured via multiple item-measurement on Likert scales were analyzed according to classical test theory and a construct mean score was calculated for each respondent (McDonald, 2013). For each construct, Cronbach's alpha (a measure of internal consistency of item scales) was calculated. Internally inconsistent items (with item-scale correlations < 0.7) were removed and all constructs reached satisfying levels of Cronbach's α > 0.7 (Table 2 and Appendix B).

Data was analyzed by using descriptive and inference statistics, i.e., by *Chisquare*-tests, ANOVAs (repeated measurement), *t*-Tests for paired samples, correlational and linear regression analyses. As measure of effect size, partial eta (η^2) is reported (Hair, 2011).

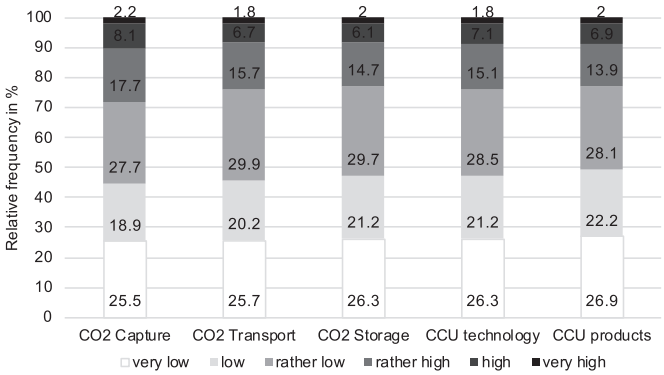

Fig. 1. Ratings of awareness (perceived information level) about CCS- and CCU-technology process-chain steps (n = 509).

3. Results

3.1. Awareness of the CCS- and CCU-technology

CCS- and CCU-awareness were measured by the perceived information level. The subjectively rated level of information about different process-steps of CCS and CCU was low to medium (M = 2.60, SD = 1.24). On a Likert-scale ranging from 1 (not informed at all) to 6 (very well-informed), the information level regarding the CCU- and CCS-technology and its respective process-steps varied between M = 2.70, SD = 1.35 (capture), M = 2.63, SD = 1.30 (transport), M = 2.59, SD = 1.29 (storage), M = 2.61, SD = 1.31 (CCU-technology), and M = 2.58, SD = 1.31 (CCU-products) (Fig. 1).

The majority (ca. 75%) of the sample reported to feel (very) uninformed about CCS and CCU and the respective process-chain steps. Only 8–10% of respondents rated their perceived information level as high to very high. CCS- and CCU-information levels did not differ significantly (p = n.s.), i.e., the knowledge about CCS and CCU in the sample was on comparably low levels.

3.2. General perceptions and acceptance of CCS and CCU

Fig. 2 shows that CCS and CCU were positively perceived, but CCU reached significantly higher acceptance ratings (M_{CCS} = 4.85, SD = 2.47, M_{CCU} = 5.63, SD = 2.51; (F(1,508) = 71.4; p < 0.01; η^2 = .123)), a more positive benefit perception (M_{CCS} = 3.6, SD = 1.12, M_{CCU} = 3.88, SD = 1.08; F(1,508) = 29.1; p < 0.01; η^2 = .54), and lower barrier perceptions (M_{CCS} = 3.9, SD = 1.01, M_{CCU} = 3.72, SD =

Table 2
Item analysis statistics (Cronbach's alpha) for the questionnaire items.

Construct	Attitudes	CCS-technology	CCU-technology
Attitude towards risks and safety	α = .76 (4 items)		
Perceived information level (CCS / CCU)	α = .97 (5 items)		
Environmentally conscious behavior	α = .81 (4 items)		
Technical self-efficacy	α = .81 (4 items)		
Personal innovativeness	α = .89 (4 items)		
Local acceptance		α = .88 (4 items)	α = .86 (4 items)
Benefits		α = .90 (2 items)	α = .95 (5 items)
Barriers		α = .90 (5 items)	α = .90 (5 items)
CO_2-capture risks		α = .88 (4 items)	α = .88 (4 items)
CO_2-transport risks		α = .85 (4 items)	α = .84 (4 items)
CO_2-(temporary) storage risks		α = .93 (8 items)	α = .91 (6 items)
CCU production risks			α = .89 (4 items)
CCU product risks			α = .90 (4 items)
CCU product disposal risks			α = .92 (5 items)
General acceptance		α = .95 (4 items)	α = .96 (4 items)

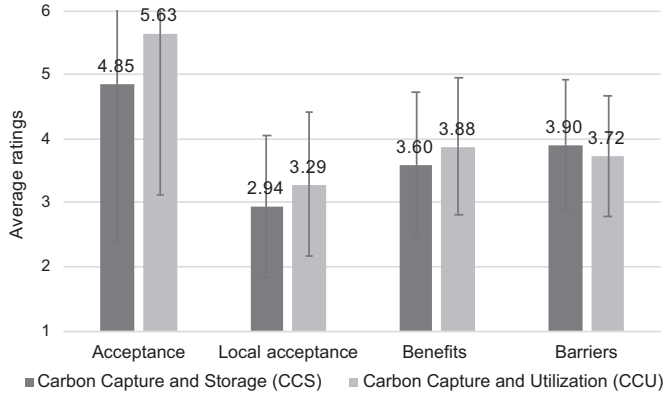

Fig. 2. Acceptance, local acceptance, benefits and barrier ratings for the CCS- and CCU-technology (n = 509). Mean values on top of the bars, error bars indicate standard deviations.

0.94; $F(1,508) = 35.7$; $p < 0.01$; $\eta^2 = .66$) than CCS. However, local acceptance decreased when either a CCS- or a CCU-site was supposed to be developed in the closer area and even turned to a slight (CCU) or even stronger (CCS) rejection ($M_{CCS} = 2.94$, $SD = 1.12$, $M_{CCU} = 3.29$, $SD = 1.12$; $F(1,508) = 64.4$; $p < 0.01$; $\eta_2 = .11$).

Chi-square tests for nominal-scaled data were performed to examine the relationship between individual factors (gender, education) and CCS/CCU-acceptance. No effects of gender or education on acceptance ratings were found, i.e., CCS- and CCU-acceptance did not differ for male or female respondents and it was not affected by different levels of educational attainment.

3.3. Risk perception for CCS- and CCU-technology process-chain steps

Respondents perceived slightly elevated risks for the process-chain steps of both technologies. Looking at the three steps "capturing", "storage", and "transport" (aggregated for CCS and CCU), CO_2-storage was perceived as the riskiest ($M = 4.08$, $SD = 0.91$), followed by CO_2-transport ($M = 3.98$, $SD = 0.92$) and capture of CO_2 ($M = 3.80$, $SD = 0.95$). T-tests for paired samples proved highly significant differences between the three process-steps CO_2-storage, transport, and capture.

Risk perceptions for each process-chain step were significantly higher for CCS than for CCU (Fig. 3); i.e. for CO_2 capturing ($M_{CCS} = 3.89$, $SD = 1.03$, $M_{CCU} = 3.68$, $SD = 1.02$; $F(1,508) = 39.1$; $p < 0.01$; $\eta^2 = .72$), CO_2-transport ($M_{CCS} = 4.03$, $SD = 0.98$, $M_{CCU} = 3.93$, $SD = 0.98$; $F(1,508) = 11.0$; $p < 0.01$; $\eta^2 = .21$), and CO_2-storage ($M_{CCS} = 4.16$, $SD = 0.97$, $M_{CCU} = 4.0$, $SD = 0.96$; $F(1,508) = 35.0$; $p < 0.01$; $\eta^2 = .64$).

Risks specifically related to CCU and its process-steps were not highly pronounced. The highest perceived CCU-related risks were reported for the disposal of CCU-products ($M_{CCU} = 3.90$, $SD = 1.01$), followed by risks associated with the production of CCU-products

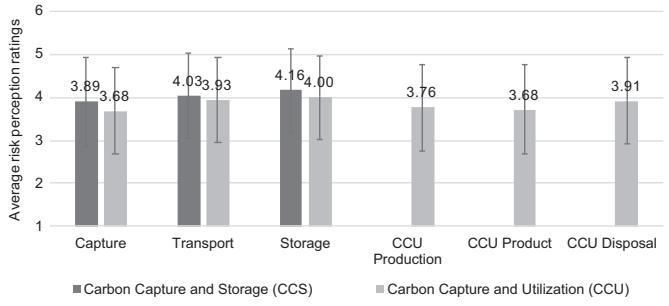

Fig. 3. Risk perception ratings for CCS- and CCU technology process-chain steps (n = 509). Mean values on top of the bars, error bars indicate standard deviations.

($M_{CCU} = 3.76$, $SD = 1.0$), and risks related to CCU-product usage itself ($M_{CCU} = 3.68$, $SD = 1.05$). T-tests for paired samples proved highly significant differences between CCU-disposal risks, CCU-production risks, and CCU-product usage risks.

Looking for acceptance "hot spots", i.e., an increased risk perception for single process-chain steps, the highest risk ratings were expressed for CO_2-storage ($M_{CCS} = 4.16$, $M_{CCU} = 4.0$) and CO_2-transport in the CCS context ($M_{CCS} = 4.03$, $M_{CCU} = 3.93$). In the CCU context, risks associated with CCU-product disposal ($M_{CCU} = 3.91$) were almost equally high as CO_2-transport risks ($M_{CCU} = 3.93$). "Hot spots" in the CCU context were CO_2-storage ($M_{CCU} = 4.0$), CO_2-transport ($M_{CCU} = 3.93$) and product disposal ($M_{CCU} = 3.91$). The lowest risks were perceived for capturing CO_2 in the CCU context and CCU-product usage (both $M_{CCU} = 3.68$).

3.4. Regression analysis on CCS and CCU-acceptance

We ran stepwise regression analyses to assess the impact of demographic characteristics, perceived information level, general benefit and risk perceptions as well as risk perceptions of the process-chain steps on general CCS- and CCU-acceptance ratings. Applying sensitivity analyses, the most parsimonious regression model for predicting CCS- and CCU-acceptance was determined by the AIC (Akaike's Information Criterion) score (Akaike, 1973). For CCS, the regression model with the predictors "CCS benefits", "local acceptance of CCS siting", "CCS storage risks", "CCS-transport risks", "general CCS barriers" showed the lowest AIC score (AIC = 437.7, excluded variables: gender, age, education, information level, CCS capture risks). For CCU, the model with the predictors "CCU benefits", "local acceptance of CCU siting", "CCU-disposal risks", "CCU-product risks", "general CCU barriers" had the lowest AIC score (AIC = 415.06, excluded variables: gender, age, education, information level, perceived risks of CO_2-capture, -transport, -storage, and production).

For the chosen models, regression diagnostics were carried out to determine if model analysis assumptions were met, if models were affected by influential observations, and if multicollinearity applied (Belsley et al., 2005). Visual diagnostics of scatterplots proved that the assumptions of linearity and homoscedasticity were met. According to the Durbin-Watson (DW) statistic, which should not strongly deviate from 2.0, independency of residuals was given in both regression models ($DW_{CCS} = 2.0$; $DW_{CCU} = 2.0$). To check for influential observations, Cook's distance (D) was calculated, which measures changes in the regression coefficient when the observation is removed. Cook's distance, which should be < 1, was $D_{maxCCS} = 0.08$ for the CCS regression model and $D_{maxCCU} = 0.09$ for the CCU regression model, i.e., both models were not affected by influential observations. Maximum leverage values were below the cut-offs (in brackets) in both models ($L_{max\ CCS} = 0.03$ (< 0.06), $L_{max\ CCU} = 0.06$ (< 0.07), indicating that there were no extreme values among the predictor variables. Multicollinearity diagnosis was run to control for biasing effects of intercorrelating predictors (Hair, 2011). For both regression models, tolerance values and the VIF (Variance Inflation Factor, values > 10 show multicollinearity, reported in Tables 3 and 4) indicated that multicollinearity could be ruled out.

The regression model for *CCS-acceptance* accounted for 61.8% of variance (100% would indicate that the regression model explains all the variability of the response data around its mean) ($F(5,508) = 165.1$; $p < 0.01$, Table 3). Stepwise regression analysis showed that sociodemographic variables such as gender, age, education, information level, and CCS capture risks were excluded from the regression model, i.e., they had no significant influence on CCS-acceptance ratings. The highest positive impact on CCS-acceptance was found for perceived CCS benefits (environmental relief and climate change mitigation) and local acceptance of CCS siting. Higher risk perceptions regarding the process-chain steps CCS storage and transport as well as perceived CCS barriers (health and environmental risks, sustainability concerns) had a

Table 3
Regression model for CCS acceptance (n = 509).

	B	SE B	ß	T	VIF	t	p
Constant	5.50	.70				7.90	0.000
CCS benefits	.73	.07	.33	0.36	1.3	10.62	0.000
Local acceptance of CCS siting	.46	.86	.21	0.35	2.03	5.32	0.000
CCS transport risks	− .41	.12	− .16	0.31	2.3	− 3.40	0.001
CCS storage risks	− .39	.14	− .15	0.24	3.1	− 2.75	0.01
CCS barriers	− .35	.95	− .14	0.29	2.0	− 3.65	0.000

Adjusted R^2 = 0.62.
R^2 = determination coefficient; B = unstandardized beta; SE B = standard error for the unstandardized beta; ß = standardized beta; T = Tolerance; VIF = Variance Inflation Factor; t = *t*-test statistics; p = probability value.

Table 4
Regression model for CCU acceptance (n = 509).

	B	SE B	ß	T	VIF	t	p
Constant	5.30	.71				7.45	0.000
CCU benefits	.92	.75	.39	0.31	1.51	12.16	0.000
CCU disposal	− .46	.14	− .19	0.22	3.55	− 3.31	0.001
CCU products	− .45	.13	− .19	0.22	3.55	− 3.35	0.001
Local acceptance of CCU siting	.30	.86	.13	0.37	2.11	3.49	0.001
CCU barriers	− .20	.09	− .07	0.34	1.83	− 2.08	0.05

Adjusted R^2 = 0.65. R^2 = determination coefficient; B = unstandardized beta; SE B = standard error for the unstandardized beta; ß = standardized beta; T = Tolerance; VIF = Variance Inflation Factor; t = *t*-test statistics; p = probability value.

negative impact on CCS-acceptance.

The regression model for *CCU-acceptance* explained 64.5% of variance ($F(5,508) = 185.9$; $p < 0.01$, Table 4). Again, sociodemographic variables (gender, age, education) and information level had no significant influence on CCU-acceptance and were excluded from the regression model. Further, perceived risks related to CO_2-capture, transport, storage, and production as CCU-technology process-steps had no impact on CCU-acceptance. General CCU benefit perceptions (environmental relief and climate change mitigation) had the highest positive effect on CCU-acceptance ratings, followed by higher levels of local acceptance of CCU siting. Lower CCU-acceptance was related to higher levels of CCU-disposal risks, CCU-product usage risks, and general CCU barriers (health and environmental risks, sustainability concerns).

In summary, the findings of the regression analyses indicate that individual perceptions of CCS- and CCU-acceptance are based on differing motive patterns. One commonality for both acceptance models is that benefit perceptions and local acceptance of CCU/CCS-siting were the strongest determinants of acceptance. However, risk perceptions impacting acceptance were different for CCU und CCS; especially regarding perceived risks related to technology process-chain steps. For CCS-acceptance, risks referring to CO_2-capturing and CO_2-transport were the most important predictors. While the same process-steps are part of the CCU process chain, CCU-acceptance was mostly influenced by perceived risks of CCU-product usage and CCU-product disposal.

3.5. Perceived benefits, barriers, and risk perceptions of CCS and CCU

The regression analysis revealed that perceived benefits and barriers as well as risk perceptions related to specific process-chain steps predicted CCS and CCU-acceptance. Now we analyze these predictors in more detail to achieve deeper insights into CCS and CCU-acceptance patterns. Methodologically, we analyzed the single items which were used as indicators for construct measurement of benefits, barriers, and technology process-chain risk perceptions.

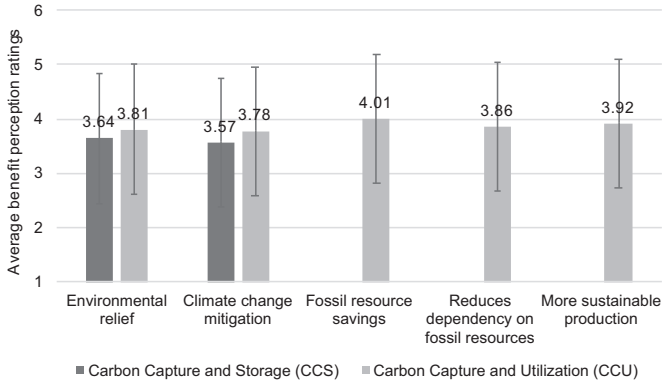

Fig. 4. Benefit perception ratings for the CCS- and CCU technology (n = 509). Mean values on top of the bars, error bars indicate standard deviations.

3.5.1. Perceived benefits of CCS and CCU

Benefit perceptions for both CO_2-based technologies were not highly pronounced. Still, CCU-benefit perceptions were significantly higher than for CCS, both, for its beneficial potential to relieve the environment ($M_{CCS} = 3.64$, $SD = 1.19$, $M_{CCU} = 3.81$, $SD = 1.19$; $F(1,508) = 9.46$; $p < 0.01$; $\eta^2 = .02$) and for its contribution to climate change mitigation: ($M_{CCS} = 3.57$, $SD = 1.17$, $M_{CCU} = 3.78$, $SD = 1.20$; $F(1,508) = 14.79$; $p < 0.01$; $\eta^2 = .03$) (Fig. 4). Further CCU-benefits were fossil resource savings ($M_{CCU} = 4.01$, $SD = 1.22$), a reduced dependency on fossil resources ($M_{CCU} = 3.86$, $SD = 1.18$), and a more sustainable production ($M_{CCU} = 3.92$, $SD = 1.56$).

3.5.2. Perceived barriers of CCS and CCU

The construct of perceived barriers exerted the smallest impact on acceptance ratings in the regression analyses. Overall, the barrier perceptions were on a moderate level (ranging between 3.7 and 4.1, Fig. 5). The comparison of single barrier perceptions yielded significantly higher barrier perceptions for CCS than for CCU. In particular, the highest concern was that CCS – and to a lower extent CCU – delay the problem of increasing emissions ($M_{CCS} = 4.11$, $SD = 1.21$, $M_{CCU} = 3.85$, $SD = 1.20$; $F(1,508) = 23.14$; $p < 0.01$; $\eta^2 = .04$), cause environmental threats ($M_{CCS} = 4.05$, $SD = 1.17$, $M_{CCU} = 3.71$, $SD = 1.10$; $F(1,508) = 42.97$; $p < 0.01$; $\eta^2 = .08$), health threats ($M_{CCS} = 3.98$, $SD = 1.18$, $M_{CCU} = 3.74$, $SD = 1.12$; $F(1,508) = 23.04$; $p < 0.01$; $\eta^2 = .04$), were perceived as prerequisite to continue burning fossil resources ($M_{CCS} = 3.80$, $SD = 1.27$, $M_{CCU} = 3.58$, $SD = 1.21$; $F(1,508) = 19.3$; $p < 0.01$; $\eta^2 = .04$), and delaying investments in other sustainable technologies ($M_{CCS} = 3.76$, $SD = 1.23$, $M_{CCU} = 3.61$, $SD = 1.14$; $F(1,508) = 8.29$; $p < 0.01$; $\eta^2 = .02$).

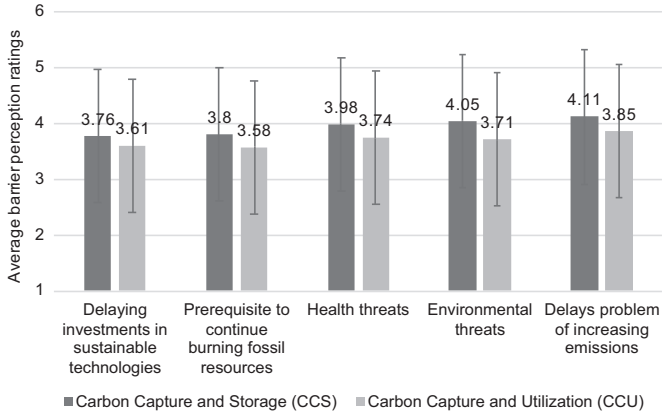

Fig. 5. Barrier perception ratings for the CCS- and CCU technology (n = 509). Mean values on top of the bars, error bars indicate standard deviations.

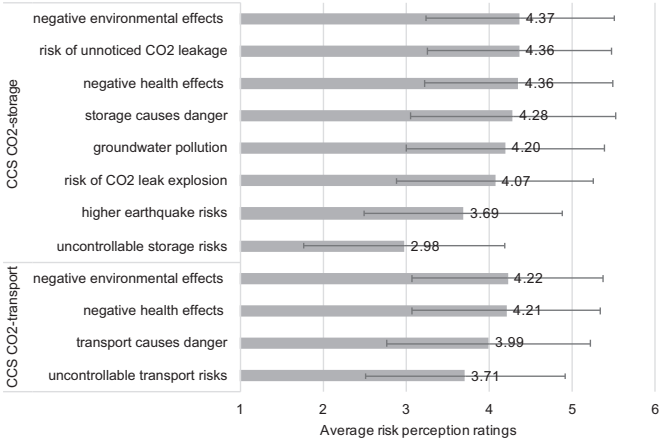

Fig. 6. Risk perception ratings (rejection = 1, affirmation = 6) regarding CO2-transport and storage in the CCS context (N = 509). Mean values on top of the bars, error bars indicate standard deviations.

3.5.3. Risk perceptions of technology process-chain steps

The most striking differences in acceptance patterns for CCS and CCU were found in the risk perceptions regarding the single technology process-chain steps. As shown in the regression analyses before, transport and storage of CO_2 were most relevant for the acceptance of the CCS-technology.

For CO_2-*transport* in the *CCS-context*, the strongest concerns referred to negative effects for the environment (M = 4.22, SD = 1.15) and health (M = 4.21, SD = 1.14), followed by associations with danger (M = 3.99, SD = 1.23) and uncontrollability (M = 3.71, SD = 1.20) (Fig. 6).

Regarding *CO_2-storage*, the perceptions were on a comparably high level: the highest concerns were expressed for negative environmental effects caused by CO_2-leakage from the storage site (M = 4.37, SD = 1.13), followed by risks of an unnoticed CO_2-leakage (M = 4.36, SD = 1.11), negative effects on human health due to CO_2-leakage (M = 4.36, SD = 1.13), general perceptions of danger related to CO_2-storage sites (M = 4.28, SD = 1.24), concerns about groundwater pollution (M = 4.20, SD = 1.19), or a CO_2-leak explosion (M = 4.07, SD = 1.18), higher earthquake risks near the storage site (M = 3.69, SD = 1.19), and general perceptions of uncontrollable risks (M = 2.98, SD = 1.21) (Fig. 6).

Referring to the previously reported findings of the regression analyses, the most acceptance-relevant process-chain steps in the context of *CCU* were product usage and product disposal.

Regarding *CCU-product usage,* all concerns were confirmed (Fig. 7), but on a moderate level. The highest concern referred to CO_2-leakage from the product surface (M = 3.73, SD = 1.16) and potential negative

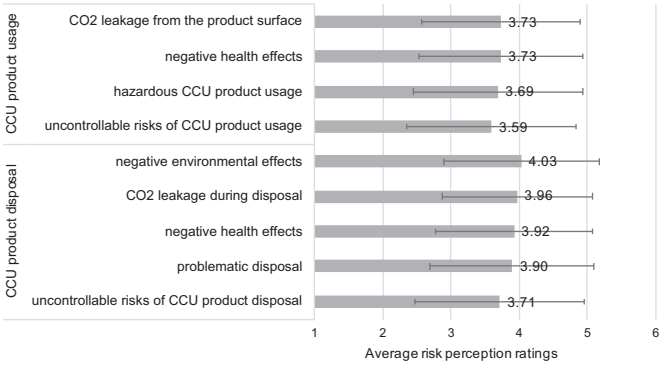

Fig. 7. Risk perception ratings (rejection = 1, affirmation = 6) regarding CCU product usage and CCU product disposal (N = 509). Mean values on top of the bars, error bars indicate standard deviations.

health effects (M = 3.73, SD = 1.20), followed by general perceptions of hazards (M = 3.69, SD = 1.24) and uncontrollable risks (M = 3.59, SD = 1.24) during CCU-product usage.

Perceived risks associated with CCU-product *disposal* were on a higher level, with negative environmental effects (e.g., release of toxic substances) during product-disposal as biggest concern (M = 4.03, SD = 1.14), followed by the concern about CO_2-release during disposal (M = 3.96, SD = 1.10), negative health effects (M = 3.92, SD = 1.15), other (unexpected) problems emerging during disposal (M = 3.90, SD = 1.20), and a general perception of uncontrollable risks caused by product-disposal (M = 3.71, SD = 1.24) (Fig. 7).

Summing up so far, the detailed analysis of acceptance-relevant benefits, barriers, and risks showed that the patterns of technology perceptions differ from each other: CCU-technology acceptance was characterized by environmental benefit perceptions (especially fossil resource savings), concerns about negative health and environmental effects, concerns about the sustainability of the technology approach, and risks associated with product usage (CO_2-leakage from the product surface) and product disposal (causing additional pollution). The analysis revealed a similar pattern regarding the general benefits and barriers involved in CCS-acceptance, but essential differences in the perception of process-chain steps. Here, concerns about health and environmental safety were the basis of CO_2-leakage fears during transport and storage, which contributed to CCS-technology acceptance.

4. Discussion

Previous studies on the acceptance of CO_2-based technologies focused either on CCS or on CCU. Even though both technologies differ regarding their technical processes and climate change mitigation effects, they are often mixed up in the public discourse. Therefore, the present study investigated perceived benefits, barriers, and risks regarding the technologies and their process-chain steps, as well as local acceptance of CCS and CCU. This investigation delivered information about how CCS and CCU are perceived, which factors influence the acceptance of both technologies, and which process-chain steps lead to specific risk concerns. The results can be used to derive information-, communication- and marketing-recommendations for policy and industry to inform citizens, local residents, or potential future customers of CO_2-derived products in a comprehensive and individually tailored manner. For technology research, the results provide target areas for which reliable information and data is required.

4.1. Public awareness and acceptance of CCS and CCU

The *awareness of CCS and CCU* was rather low in our sample, which is in line with the awareness levels found in other studies (Duetschke et al., 2014; Perdan et al., 2017a). Approx. 75% of the sample reported only a limited knowledge about both technologies. Since subjective ratings were used to assess the awareness levels, the knowledge level found here might still be an overestimation due to biasing answering effects of social desirability (Fisher, 1993). Also, we cannot estimate the impact of factual technical knowledge on acceptance and its relation to the self-assessment of technology-related knowledge. Future studies should therefore supplement the subjective awareness-reports with a more factual, domain-knowledge-based assessment. Even though respondents had only limited knowledge about the technical concept of both technologies and their evaluations should thus be regarded as initial reactions, they positively evaluated both CO_2-based technologies, with an even more positive reaction towards the CCU-technology. We are aware of the fact that the initial reactions assessed in the survey might reflect “pseudo-opinions”, i.e., weak and nonstable opinions, which might change when additional information is provided, or the topic gets more visible in the public discourse. However, this does not limit the validity of the outcomes: Since innovative technologies are

usually unknown to the public in the development phase, these initial reactions of (mostly) laypeople in our sample can serve as valuable indicator for the initial public reaction after technology roll-out. Since we cannot exclude that a better-informed public might evaluate the CCS- and CCU-technology differently, further formative acceptance studies are needed to accompany planned CCS/CCU communication strategies in the public.

Recent studies also found positive perceptions of CCU (Arning et al., 2017; Jones, 2015; Perdan et al., 2017a; van Heek et al., 2017a), especially acknowledging its contribution to climate change mitigation targets. Based on our findings, climate mitigation effects of CCU were also acknowledged, but saving fossil resources and reducing the dependencies on fossil resources are perceived as even stronger beneficial effects of CCU. CCU communication should therefore not only focus on CCU as element of a climate change mitigation strategy but also on fossil resource savings as key factors of CCU benefit perception. Interestingly, CCS was also perceived positively by our sample. Even though the positive perception of CCS is in contrast with findings of other studies (Lock et al., 2014; Upham and Roberts, 2011), single studies also report slightly positive attitudes towards CCS (Yang et al., 2016). We hypothesize that CCS was forgotten by the German public in recent years since it is not pursued further as technology option in Germany and does not receive much attention in the public anymore.

Differences between CCS- and CCU-acceptance became more visible when looking at local acceptance of CCS- and CCU-deployment. Acceptance considerably dropped, when respondents (hypothetically) became personally affected by CCS- or CCU-sites located in the neighborhood. Local acceptance of CCS-sites was lower than for CCU-sites. These perception patterns are in line with other findings, either showing a support for national CCU deployment (Perdan et al., 2017a) or a negative local acceptance of CCS-siting (Terwel et al., 2012). It should be noted here that the comparably small statistical effect sizes of mean differences (Fritz et al., 2012) between CCS and CCU evaluations indicate that the differences between CCU and CCS-acceptance is not too large. We assume that the low level of awareness and ability to differentiate both technologies by laypeople led to moderate ratings for CCS and CCU, which were not far apart – but are still highly significant due to the large sample size.

In line with acceptance models in the context of renewable energy technologies (e.g., Huijts et al., 2012), perceived *benefits* had the biggest positive impact on the acceptance of both CO_2-based technologies. Benefit perceptions of CCU were mainly shaped by its potential to relieve the environment, its contribution to climate chance change mitigation and by its potential in saving fossil resources. Hence, CCU-communication activities should focus on these aspects to promote public acceptance.

4.2. The technology process-chain of CCS and CCU

The inclusion of *technology process-chain steps* into the evaluation provided a more detailed picture regarding the acceptance of both CO_2-based technologies. For CCS, the transport and storage of CO_2 were identified as “hot spots” affecting CCS-acceptance. This result is corroborated by findings from Upham and Roberts (2011) on CCS risk perception, which also found storage to be associated with a higher risk compared to transport and capture of CO_2.

Interestingly, risk perceptions of the CCU-technology process-chain did not focus on aspects of the technical infrastructure (CO_2 capturing, transport and storage), even if they are largely the same as for CCS. For CCU, perceived risks were the highest for the handling of products derived from CO_2. For CCU, product usage and disposal were identified as critical “hot spots”, which corresponds to findings for potential CCU-product consumers (Arning et al., 2017; van Heek et al., 2017a), where product-related risks were highly acceptance-relevant, but the infrastructural part of the CCU-technology was blanked out in evaluations. Regarding CCU-product *usage*, risk perceptions were formed by concerns about negative health- and environmental effects due to CO_2-leakage (e.g., allergies, headaches as negative health effects or toxic substances polluting the environment). Even though CO_2-leakage from a stable CCU-product is technically not possible, inadequate and incorrect mental models of laypeople determine subjective perceptions and, consequently, CCU-product acceptance. To enhance the market potential of CO_2-based products, comprehensive and reliable information has to be conveyed to consumers about the usage of CO_2 as feedstock, and consumer trust has to be promoted by transparent communication activities.

Another acceptance-relevant “hot spot” of CCU-product acceptance, which was hardly considered in CCU-related acceptance research yet, is the *disposal stage* of CCU-products. Potential CCU-product consumers are highly skeptical about the sustainability of the CCU-technology, because the CO_2 will be released again after the CCU-product gets disposed. This concern is mirrored in the scientific community where the benefits of CCU are often expected from (temporary) storage of CO_2 (Mac Dowell et al., 2017) while the actual benefits of CCU are more often due to replacing fossil feedstocks (Artz et al., 2018). On top, potential CCU-product consumers are concerned about additional polluting effects of CCU-product disposal. This aspect is of special importance since technical assessments of the CCU-technology (e.g. in life cycle assessments) often do not integrate this stage into their assessments by focusing on so-called cradle-to-gate comparisons (Von der Assen and Bardow, 2014). From a technical perspective, the disposal of CCU-products is not relevant in comparative life cycle assessments if the CCU-products are identical to the conventionally produced products. In this case, the disposal has the same effects for CCU-products as for the conventionally produced products. However, as it was shown by regression analyses, the disposal stage is highly acceptance-relevant from the public perception perspective. This emphasizes the necessity to extend and intensify the research collaboration between engineering and social science (Jones and Jones, 2016) and to include public perceptions and acceptance as a variable into early development stages of innovative sustainable technologies.

4.3. Conclusions and policy implications

Based on the analysis of CCS- and CCU-perceptions and their specific acceptance patterns, valuable implications can be derived for further deployment of the CCU-technology. The results of the survey point out that the public, at least in Germany, is not familiar with CO_2-based technologies, but – based on a very low level of information – shows a positive attitude regarding CCU. Compared to the previous negative public image of CCS, especially in Germany (Fischer, 2015), the general perception of CCS was also rather positive. However, results do not imply that an immediate roll-out of CCU and CCS in Germany would be possible. Apart from technical advancements of CCU, a strong focus on innovation- and risk communication for CCU is needed. So far, existing communication is rare and mainly directed on CCS with a techno-centric framing, while neglecting economic, political, institutional and social aspects of CCS (Corry and Reiner, 2016). One priority is therefore the installation of information channels for the public which communicate scientific advances as well as developments by industry. Social media technologies can play an important role in this context because they allow (if well-designed) an authentic, transparent and accessible presentation of information on sustainable technologies for the public (Reilly and Hynan, 2014). At least as important is the content of CCS-/CCU information, which should a) convey the environmental benefits of CCU as strongest promotors of acceptance, b) elevate local acceptance of CCU- or CCS-sites by participatory approaches, and c) transport different messages in communication depending on the respective technologies. For CCS-deployment, the aspects of CO_2-transport and -storage are the most acceptance-relevant and need to be transparently addressed in technical infrastructure planning, decision-making processes, and information activities. For

CCU-deployment, a focus on the consumer- and product-level is necessary: For CCU-products, the same legal requirements and testing procedures regarding harmful substances and health compatibility apply as for conventionally manufactured products. Here, product-quality seals, which are awarded by industry-independent institutions, might act as trust-enhancing measures (Atkinson and Rosenthal, 2014).

Moreover, the relationship between public acceptance and public (dis)trust regarding the economic or ecologic motivation of industry, which is engaged in CCS/CCU activities, requires further research. For CCS it was found that laypeople's trust in stakeholders affects their acceptance of CCS implementation: trust in environmental NGOs was higher than industrial stakeholders (Terwel et al., 2011). For the CCU-technology, recent data corroborates that distrust in stakeholders can reduce acceptance (van Heek et al., 2018). Distrust in industrial and policy authorities was explained by the assumption that stakeholders were only interested in their own commercial profit, thereby neglecting interests of the public.

A final implication refers to CCU-product disposal: public concerns about a reduced sustainability of CCU, when CO_2 is released at the end of the product life-cycle, need to be addressed, e.g., by setting the same disposal standards as for conventional products. As long as sustainability concerns regarding CCU remain unanswered, a broad public acceptance of CCU-deployment will not be achieved.

4.4. Methodological considerations

Since the survey was run as an online survey, with respondents coming from a pre-recruited online panel of a market research company, we cannot exclude a sample selection bias, which reduces the generalizability of findings to the whole population. Even though the bias of convenient sampling in the university context (especially young and highly educated respondents) could be ruled out due to census-representative sampling (quotas for age, gender, education, and region), the findings could be biased by effects of self-selection. Self-selection means that respondents who chose to participate in the survey, do not necessarily represent the entire target population. Therefore, the findings presented here should be interpreted considering this self-selection bias.

In the survey, respondents gave their ratings in a forced-choice-format, where they had to consider risk aspects of different process-steps. Participants had to evaluate risks that were predefined by the questionnaire; maybe they would not have thought of the presented risks by themselves, but perceived other risks. This “forced choice” answering format might have led to an overestimation of risk ratings. However, in our preceding qualitative studies, respondents mainly reported health and environmental fears related to the CCU technology infrastructure and CCU-product usage (Arning et al., 2017). Therefore, we are quite confident that the presented risk categories contained valid and acceptance-relevant risk and benefit factors.

Regarding the assessment of local acceptance, respondents evaluated a hypothetical scenario of a CCS- or CCU-site in their neighborhood. Here, it is important to consider that no conclusion can be drawn regarding local opposition or support to specific and real CCS- and CCU-sites. With an ongoing deployment of the CCU-technology, the study should be replicated by asking directly-affected residents living near CCS- or CCU-sites.

A further methodological constraint refers to the different number of items used for the assessment of risks related to the CCS- and CCU-technology process-chain steps. Risks regarding capture, transport, production, and CCU-product usage were assessed by using similarly formulated items (i.e., “not dangerous”, “harmful to human health”, “harmful to the environment”, “controllable”). Risks concerning storage and disposal were evaluated using items that considered more precise aspects (e.g., explosion, earthquakes), which were mentioned by participants in our preceding qualitative studies. We cannot exclude that these item content differences might have caused higher risk perceptions. However, to get insights into the nature of CCS- and CCU-acceptance patterns, we decided to loosen the methodological control in questionnaire design and use items with differing content.

Finally, as pointed out by a reviewer, the technical instructional text about the CCS- and CCU technology was designed in a neutral way, leaving out potential risks and benefits to avoid biases in the evaluation of both of both technologies. One objection might be that the neutral tone of the instructional text led to an underestimation of risks in the evaluation of both technologies. However, since not only risks, but also benefits were not described in the instruction, we assume that this error was constant for both (positive and negative) directions.

4.5. Future steps

For CCS, socio-political factors such as (dis)trust in stakeholders and perceived procedural unfairness have been found to affect CCS-acceptance directly and indirectly as moderating effect (L’Orange Seigo et al., 2014; Terwel et al., 2012). Issues of trust in stakeholders could also be important for CCU-acceptance, as recent data suggests (van Heek et al., under review), therefore further research should examine the impact of (dis)trust in stakeholders (science, policy, NGOs, industry) on CCU-acceptance.

The impact of individual factors such as environmental awareness, innovativeness or technical self-efficacy on CCU-acceptance has not been analyzed in this study. Future analyses should answer the question if acceptance and acceptance-relevant factors of CCU differ among individuals and derive meaningful segments of profiles of (non)adopter-groups.

The investigation of CCU-acceptance should also be extended regarding the acceptance-indicators used for quantifying CCU-acceptance. So far, acceptance was mainly operationalized by the measurement of risk and benefit perceptions or cognitively based evaluations. Future research should therefore also integrate the affective dimension of acceptance (e.g., by using semantic differentials, where the connotative meaning of a technology is assessed via ratings of bipolar adjective pairs).

In addition, next steps will be directed to an integration of technical assessment- and acceptance-factors within one frame of reference. This allows to integrate acceptance as weighting parameter into scenario-design and to determine the cut-offs between technical variables and an acceptable design of CCS- and CCU-technology-scenarios.

Finally, it should be noticed that Germany takes a special role as the implementation of CCS plants was stopped by public protests and the commercial implementation of CCS failed (Fischer, 2015). Thus, a consideration is necessary whether a more critical attitude towards CCU is a result of the rejection of CCS in Germany. A more region-specific analysis of CCU perceptions should be conducted, contrasting perceptions from different areas in Germany (e.g., urban vs rural, regions which have been locally affected by CCS projects, effects of the economic situation and political climate in the federal states of Germany). Moreover, residents of other countries might show different perceptions of CCS/CCU benefits, barriers, and risks. Hence, we intend to conduct our study in other countries to compare CCS/CCU-acceptance and perceptions depending on different countries, cultures, and societal values.

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Appendix A

General Introduction (at the beginning of the survey)

Dear Ladies and Gentlemen, thank you for your interest in this survey!

Climate protection is one of the greatest global challenges today. CO_2 in the atmosphere is considered a major driver of climate change. Therefore, reducing CO_2 emissions is seen as an important measure of mitigating climate change.

One way to reduce CO2 emissions is to capture CO2 directly from large sources such as power plants and transport it to storage sites (typically geological rock formations), where CO_2 is permanently stored underground. The process of capturing and storing CO_2 is known as *CCS (Carbon Capture and Storage)*.

In addition to permanent storage, sensible use of the separated CO_2 is possible as well - for example, as raw material for the production of plastics or fuel. The process of capturing and using CO2 for products is called *CCU (Carbon Capture and Utilization)*.

Below you will find several questions about your attitude regarding CCS and CCU topics. No technical experience with CCS or CCU is necessary to answer the questions. Please answer the questionnaire conscientiously and completely. Only your personal opinion matters, there are no right or wrong answers. All data will be processed and analyzed anonymously and are subject to data protection.

You can usually choose from several answer options to answer the questions. If you are not sure which answer option to choose we ask you to choose the answer that comes closest to your opinion. You will need apporx. 15 min to fill in the questionnaire.

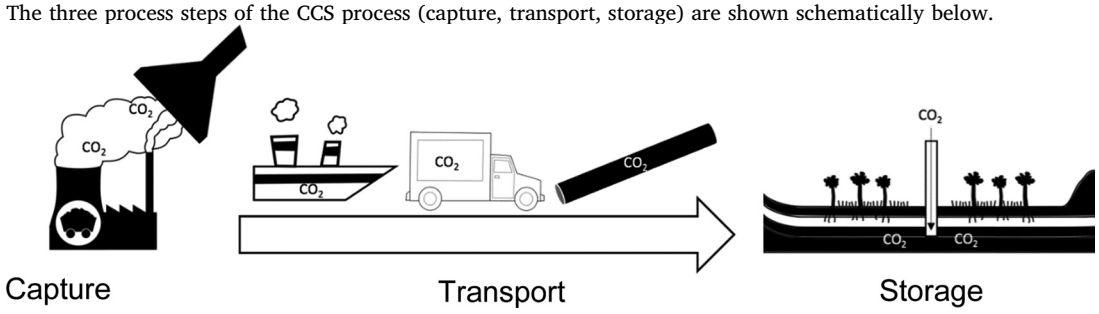
Thank you for your participation!

Introduction of Carbon Capture and Storage (CCS) (at the beginning of the CCS evaluation block)

The following part is about your personal opinion on CCS (Carbon Capture and Storage).

Carbon capture and storage (CCS) is the process of capturing waste carbon dioxide (CO2) from large point sources, such as fossil fuel power plants, and transporting it by pipelines, trucks or ships to a storage site, where the CO_2 is permanently stored. Underground geological formations are typically used as storage sites such as depleted reservoirs of oil and natural gas or deep, saltwater-bearing rock strata.

The three process steps of the CCS process (capture, transport, storage) are shown schematically below.



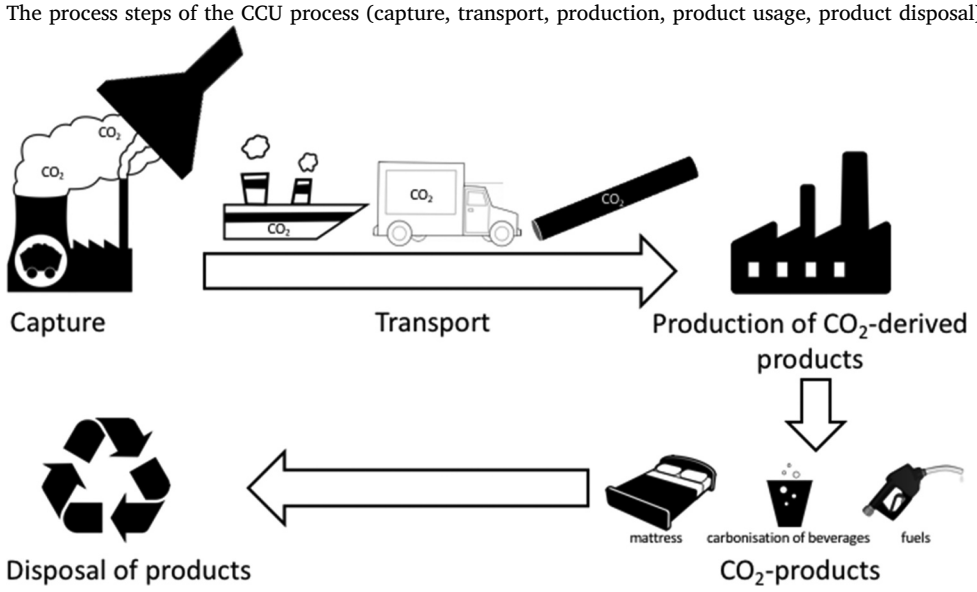
Introduction of Carbon Capture and Utilization (CCU)

(at the beginning of the CCU evaluation block)

CCU is a technology, where CO_2 emitted from carbon-intensive processes, for example by fossil fuel power generation, is used as a feedstock for the manufacture or other products.

After capturing CO_2 from large emitting sources such as power plants, the CO_2 is transported by ship, truck, or via pipeline to a production facility and temporarily stored in storage tanks, before it is supplied as resource for further processing. There are diverse options of CO_2 utilization: chemical usage (e.g., polyols such as a mattress), biological usage (e.g., fuels), and direct use (e.g., carbonization of beverages). Finally, the products are used by customers and are disposed at the end of their life cycle.

The process steps of the CCU process (capture, transport, production, product usage, product disposal) are shown schematically below.



The global need for CO_2 for the manufacture of CO_2-derived products is clearly lower than the worldwide annual amount of CO_2 emissions. Thus, CCU focuses not on the reduction of CO_2 emissions of power plants, but rather on savings of fossil resources (such as mineral oil and natural gas) for the manufacture of products. Additionally, less additional CO_2 emissions are released during the manufacture of CO_2-derived products compared to the manufacture of conventional products as the used CO_2 substitutes other emission-intensive source materials.

Appendix B

Items used for construct measurement in the survey and descriptive statistics (mean and standard deviations) for the whole sample (n = 509). Items marked with * were excluded from statistical analysis after reliability analysis (item-scale correlations < .7)

(Please note: The item numbering in Appendix B and C does not correspond to the numbering of items in the online-questionnaire, but it is used here to facilitate the identification of the corresponding German and English items.)

Item No.	Constructs	Items	M	SD	N
1	*Attitude towards risk and safety*	I am quite cautious when I make plans and when I act on them.	4.0	1.1	509
2		I follow the motto: "Nothing ventured, nothing gained".	3.1	1.2	509
3		I do not like adventurous decisions.	4.0	1.3	509
4		I like to risk something.	2.6	1.2	509
5	*Perceived information level about CCS and*	I feel well informed about the capture of CO_2.	2.7	1.3	509
6	*CCU*	I feel well informed about the transport of CO_2.	2.6	1.3	509
7		I feel well informed about the storage of CO_2.	2.6	1.3	509
8		I feel well informed about the utilization of CO_2.	2.6	1.3	509
9		I feel well informed about the utilization of CO_2 as a raw material for the production of plastics.	2.6	1.3	509
10	*Environmentally conscious behavior*	I pay attention to a low energy consumption when buying household appliances.	5.0	0.9	509
11		I try to reduce waste by avoiding unnecessary packaging, unnecessary plastic bags etc.	4.8	1.1	509
12		I specifically buy products with minimal environmental impact in manufacturing and usage.	3.9	1.2	509
13		When buying textiles, I make sure that they do not contain any pollutants.	4.0	1.3	509
14		*I prefer using public transport instead of using my car.	–	–	–
15	*Technical self-efficacy*	I can solve few technical problems alone, that I am faced with.	4.0	1.2	509
16		It's fun to crack a technical problem.	3.7	1.3	509
17		Because I have coped well with previous technical problems, I look optimistically forward to future technical problems.	4.2	1.1	509
18		I feel so helpless about technical problems that I prefer to keep my hands off them.	2.3	1.3	509
19	*Personal innovativeness regarding technol-*	I am interested in novel products.	3.6	1.4	509
20	*ogies*	I often look for information about novel technologies and products, that may interest me.	3.6	1.4	509
21		I am usually the first in my circle of friends who buys novel products.	2.9	1.5	509
22		I find it interesting to interact with novel products.	4.3	1.2	509
	CCS part				
23	*Local acceptance CCS*	I would welcome the construction of a CCS plant in my neighborhood.	2.6	1.2	509
24		I would protest against the construction of a CCS plant.	3.4	1.4	509
25		I think a CCS plant in my neighborhood is harmless.	2.8	1.2	509
26		I would be concerned if a CCS plant would be built in my neighborhood.	4.1	1.3	509
27	*CCS benefits*	Generally, CCS represents a relief for the environment.	3.6	1.2	509
28		This technology contributes to the fight against climate change.	3.6	1.2	509
29	*CCS barriers*	CCS only delays the problem of increasing emissions.	4.1	1.2	509
30		CCS represents a hazard to the environment.	4.0	1.2	509
31		The expansion of renewable energies will be delayed by investments in CCS projects.	3.8	1.2	509
32		This technology is merely a pretext to continue burning fossil energy sources.	3.8	1.3	509
33		CCS represents a hazard to the environment.	4.0	1.2	509
34	*CCS capture risks*	I think a CO_2 capture plant is harmless.	3.0	1.2	509
35		The capture of CO_2 could have negative consequences for human health.	4.0	1.2	509
36		The capture of CO_2 could have negative consequences for the environment	4.0	1.2	509
37		I think the risks of a CO_2 capture plant are controllable.	3.3	1.2	509
38	*CCS transport risks*	I think the transport of CO_2 is harmless.	3.0	1.2	509
39		Leakage of CO_2 during transport could have negative consequences for human health.	4.2	1.1	509
40		Leakage of CO_2 during transport could have negative consequences for the environment	4.2	1.2	509
41		I think the risks of the CO_2-transport are controllable.	3.3	1.2	509
42	*CCS storage risks*	I think a CO_2 storage plant is harmless.	2.7	1.2	509
43		CO_2 could explosively leak from the storage plant to the surface.	4.1	1.2	509
44		CO_2 could leak unnoticed and steadily from the storage plant to the surface.	4.4	1.1	509
45		Leakage of CO_2 from the storage plant could have negative consequences for human health.	4.4	1.1	509
46		Leakage of CO_2 from the storage plant could have negative consequences for the environment	4.4	1.1	509
47		The geological storage of CO_2 could lead to earthquakes in the area of the storage plant.	3.7	1.2	509
48		The geological storage of CO_2 could cause pollution of the groundwater.	4.2	1.2	509
49		I think the risks of a CO_2 storage plant are controllable.	3.0	1.2	509
50	*Acceptance of CCS*	I think CCS is useful.	5.0	2.5	509
51	*(min =1, max = 10)*	I think CCS is valuable.	5.1	2.4	509
52		I think CCS is acceptable.	4.8	2.5	509
53		I think CCS is free of risks.	4.2	2.3	509
54		*I think CCS is eco-friendly.	–	–	–
	CCU part				
55	*Local acceptance CCU*	I would welcome the construction of a CCU plant in my neighborhood.	2.9	1.3	509
56		I would protest against the construction of a CCU plant.	3.2	1.4	509
57		I think a CCU plant in my neighborhood is harmless.	3.1	1.3	509
58		I would be concerned if a CCU plant would be built in my neighborhood.	3.7	1.4	509
59	*CCU benefits*	Generally, CCS represents a relief for the environment.	3.8	1.2	509

60		This technology contributes to the fight against climate change.	3.8	1.2	509
61		CCU helps to save fossil resources such as oil and natural gas.	4.0	1.2	509
62		CCU helps to reduce dependence on fossil resources and their prices.	3.9	1.2	509
63		CCU represents a first step towards a more sustainable production.	3.9	1.2	509
64	*CCU barriers*	There are more useful technologies than CCU to replace crude oil as resource.	3.8	1.1	509
65		CCU only delays the problem of increasing emissions.	3.9	1.2	509
66		CCU represents a hazard to the environment.	3.7	1.1	509
67		The expansion of renewable energies will be delayed by investments in CCS projects.	3.6	1.1	509
68		This technology is merely a pretext to continue burning fossil energy sources.	3.6	1.2	509
69		CCU represents a hazard to the environment.	3.7	1.1	509
70	*CCU capture risks*	I think a CO_2 capture plant is harmless.	3.2	1.2	509
71		The capture of CO_2 could have negative consequences for human health.	3.7	1.2	509
72		The capture of CO_2 could have negative consequences for the environment	3.7	1.2	509
73		I think the risks of a CO_2 capture plant are controllable.	3.5	1.2	509
74	*CCU transport risks*	I think the transport of CO_2 is harmless.	3.1	1.2	509
75		Leakage of CO_2 during transport could have negative consequences for human health.	4.1	1.1	509
76		Leakage of CO_2 during transport could have negative consequences for the environment	4.1	1.1	509
77		I think the risks of the CO_2-transport are controllable.	3.4	1.2	509
78	*CCU (temporary) storage risks*	I think a CO_2 storage plant is harmless.	3.0	1.2	509
79		CO_2 could explosively leak from the storage plant to the surface.	3.9	1.2	509
80		CO_2 could leak unnoticed and steadily from the storage plant to the surface.	4.1	1.1	509
81		Leakage of CO_2 from the storage plant could have negative consequences for human health.	4.1	1.1	509
82		Leakage of CO_2 from the storage plant could have negative consequences for the environment	4.2	1.1	509
83		I think the risks of a CO_2 storage plant are controllable.	3.3	1.2	509
84	*CCU production risks*	I think the production process is harmless.	3.2	1.2	509
85		The production process could have negative consequences for human health.	3.8	1.1	509
86		The production process could have negative consequences for the environment	3.9	1.1	509
87		I think the risks of the production process are controllable.	3.4	1.2	509
88	*CCU product risks*	I think CO_2-products are harmless.	3.3	1.2	509
89		CO_2-products could have negative consequences for human health.	3.7	1.2	509
90		CO_2 could leak from the surface of the product.	3.7	1.2	509
91		I think the risks of CO_2-products are controllable.	3.4	1.2	509
92	*CCU product disposal risks*	I think the disposal of CO_2-products is harmless.	3.1	1.2	509
93		The disposal of CO_2-products could have negative consequences for human health.	3.9	1.2	509
94		The disposal of CO_2-products could have negative consequences for the environment	4.0	1.1	509
95		I think the risks of the CO_2 product disposal are controllable.	4.0	1.1	509
96	*Acceptance of CCU*	I think CCU is useful.	5.8	2.5	509
97	*(min = 1, max = 10)*	I think CCU is valuable.	5.7	2.5	509
98		I think CCU is acceptable.	5.6	2.5	509
99		I think CCU is free of risks.	4.7	2.3	509
100		* I think CCU is eco-friendly.	–	–	–

Appendix C

Original (german) version of the questionnaire (Please note: The item numbering in Appendix B and C does not correspond to the numbering of items in the online-questionnaire, but it is used here to facilitate the identification of the corresponding German and English items.)

Item Nr.	Constructs	Items
1	*Einstellung zu Risiko und Sicherheit*	Ich bin sehr vorsichtig, wenn ich Pläne mache und diese ausführe.
2		Ich folge dem Motto "Wer nicht wagt, der nicht gewinnt".
3		Ich mag keine abenteuerlichen Entscheidungen.
4		Ich setze gerne etwas auf's Spiel.
5	*Subjektiver Wissensstand zu CCS und*	Ich fühle mich gut über die Abscheidung von CO_2 (Abscheidung) informiert.
6	*CCU*	Ich fühle mich gut über den Transport von CO_2 informiert.
7		Ich fühle mich gut über die Speicherung von CO_2 (Speicherung) informiert.
8		Ich fühle mich gut über die Nutzung von CO_2 (CCU) informiert.
9		Ich fühle mich gut über die Verwendung von CO_2 als Rohstoff für die Herstellung von Kunststoffen informiert.
10	*Umweltbewußtsein*	Ich achte beim Kauf von Haushaltsgeräten auf einen niedrigen Energieverbrauch.
11		Ich versuche, Müll durch unnötige Verpackung, unnötige Plastiktüten etc. zu vermeiden.
12		Ich kaufe gezielt Produkte, die bei ihrer Herstellung und Nutzung die Umwelt nur gering belasten.
13		Ich achte beim Kauf von Textilien darauf, dass sie keine Schadstoffe enthalten.
14		*Ich nutze lieber öffentliche Verkehrsmittel, anstatt mit dem Auto zu fahren.
15	*Kontrollüberzeugung im Umgang mit*	Ich kann ziemlich viele der technischen Probleme, mit denen ich konfrontiert bin, allein lösen.
16	*Technik*	Es macht mir richtig Spaß, ein technisches Problem zu knacken.
17		Weil ich mit bisherigen technischen Problemen gut zurecht gekommen bin, blicke ich auch künftigen technischen Problemen optimistisch entgegen.
18		Ich fühle mich technischen Geräten gegenüber so hilflos, dass ich die Finger von ihnen lasse.
19	*Interesse an Innovationen*	Ich halte regelmaäßig Ausschau nach neuen Produkten.
20		Ich suche oft nach Informationen zu neuen Produkten, die mich interessieren könnten.
21		Ich bin meistens der Erste in meinem Freundes- und Bekanntenkreis, der neue Produkte ausprobiert.
22		Ich finde es interessant, neue Produkte auszuprobieren.
	CCS-Abschnitt	
23	*Lokale CCS-Akzeptanz*	Ich würde den Bau einer CO_2-Speicherstätte in meiner Nachbarschaft begrüßen.
24		Ich würde gegen den Bau protestieren.
25		Ich finde eine CO_2-Speicherstätte in meiner Nachbarschaft ungefährlich.

26		Ich wäre besorgt, wenn in meiner Nachbarschaft eine solche Speicherstätte errichtet würde.
27	*CCS-Vorteile*	Die CCS-Technologie bedeutet allgemein eine Entlastung für die Umwelt.
28		Die CCS-Technologie trägt dazu bei, den Klimawandel zu bekämpfen.
29	*CCS-Barrieren*	Die Speicherung von CO_2 zögert das Problem der zunehmenden Emissionen nur heraus.
30		Die CCS-Technologie birgt Gefahren für die Umwelt.
31		Durch Investitionen in Projekte zur CO_2- Speicherung wird der Ausbau der erneuerbaren Energien verzögert.
32		Die CCS-Technologie ist nur ein Vorwand, um weiter fossile Energieträger verbrennen zu können.
33		Die CCS-Technologie birgt Gefahren für die menschliche Gesundheit.
34	*Risiken CCS-Abscheidung*	Ich finde eine CO_2-Abscheidungsanlage ungefährlich.
35		Die Abscheidung von CO_2 könnte negative Folgen für die menschliche Gesundheit haben.
36		Die Abscheidung von CO_2 könnte negative Folgen für die Umwelt haben.
37		Ich finde die Risiken einer CO_2- Abscheidungsanlage kontrollierbar.
38	*Risiken CCS-Transport*	Ich finde den Transport von CO_2 zur Speicherstätte ungefährlich.
39		Ein Austritt des CO_2 während des Transports könnte negative Folgen für die menschliche Gesundheit haben.
40		Ein Austritt des CO_2 während des Transports könnte negative Folgen für die Umwelt haben.
41		Ich finde die Risiken des Transports von CO_2 zur Speicherstätte kontrollierbar.
42	*Risiken CCS-Speicherung*	Ich finde eine CO_2- Speicherstätte ungefährlich.
43		CO_2 könnte explosionsartig aus der Speicherstätte an die Oberfläche austreten.
44		CO_2 könnte unbemerkt und stetig aus der Speicherstätte an die Oberfläche austreten.
45		Ein Austritt des CO_2 aus der Speicherstätte könnte negative Folgen für die menschliche Gesundheit haben.
46		Ein Austritt des CO_2 aus der Speicherstätte könnte negative Folgen für die Umwelt haben.
47		Durch die geologische Speicherung von CO_2 könnte es zu Erdbeben in der Umgebung der Speicherstätte kommen.
48		Durch die geologische Speicherung von CO_2 könnte es zu einer Verschmutzung des Grundwassers kommen.
49		Ich finde die Risiken einer CO_2-Speicherstätte kontrollierbar.
50	*CCS- Akzeptanz*	Ich denke, CCS ist nützlich.
51	*(min =1, max = 10)*	Ich denke, CCS ist vorteilhaft.
52		Ich denke, CCS ist akzeptabel.
53		Ich denke, CCS ist frei von Risiken.
54		* Ich denke, CCS ist umweltfreundlich.
	CCU-Abschnitt	
55	*Lokale CCU-Akzeptanz*	Ich würde den Bau einer Anlage zur CO_2- Nutzung in meiner Nachbarschaft begrüßen.
56		Ich würde gegen den Bau protestieren.
57		Ich finde eine Anlage zur Nutzung von CO_2 in meiner Nachbarschaft ungefährlich.
58		Ich wäre besorgt, wenn in meiner Nachbarschaft eine solche Anlage errichtet würde.
59	*CCU-Vorteile*	Die CCU-Technologie bedeutet allgemein eine Entlastung für die Umwelt.
60		Die CCU-Technologie trägt dazu bei, den Klimawandel zu bekämpfen.
61		Die CCU-Technologie trägt dazu bei, fossile Ressourcen wie Erdöl und Erdgas einzusparen.
62		Die CCU-Technologie hilft dabei, Abhängigkeiten von fossilen Ressourcen und deren Preisen zu reduzieren.
63		Die CCU-Technologie ist ein erster Schritt hin zu einer nachhaltigeren Produktion.
64	*CCU-Barrieren*	Es gibt sinnvollere Technologien als CCU, um Erdöl als Rohstoff zu ersetzen.
65		Die CCU-Technologie zögert das Problem der zunehmenden Emissionen nur heraus.
66		Die CCU-Technologie birgt Gefahren für die Umwelt.
67		Durch Investitionen in Projekte zur CO_2- Nutzung wird der Ausbau der erneuerbaren Energien verzögert.
68		Die CCU-Technologie ist nur ein Vorwand, um weiter fossile Energieträger verbrennen zu können.
69		Die CCU-Technologie birgt Gefahren für die menschliche Gesundheit.
70	*Risiken CCU-Abscheidung*	Ich finde eine CO2- Abscheidungsanlage ungefährlich.
71		Die Abscheidung von CO_2 könnte negative Folgen für die menschliche Gesundheit haben.
72		Die Abscheidung von CO_2 könnte negative Folgen für die Umwelt haben.
73		Ich finde die Risiken einer CO_2-Abscheidungsanlage kontrollierbar.
74	*Risiken CCU-Transport*	Ich finde den Transport von CO_2 zur Speicherstätte ungefährlich.
75		Ein Austritt des CO_2 während des Transports könnnte negative Folgen für die menschliche Gesundheit haben.
76		Ein Austritt des CO_2 während des Transports könnte negative Folgen für die Umwelt haben.
77		Ich finde die Risiken des Transports von CO_2 zur Speicherstätte kontrollierbar.
78	*Risiken CCU-Speicherung*	Ich finde eine CO_2-Speicherstätte ungefährlich.
79		CO_2 könnte explosionsartig aus der Speicherstätte an die Oberfläche austreten.
80		CO_2 könnte unbemerkt und stetig aus der Speicherstätte an die Oberfläche austreten.
81		Ein Austritt des CO_2 aus der Speicherstätte könnte negative Folgen für die menschliche Gesundheit haben.
82		Ein Austritt des CO_2 aus der Speicherstätte könnte negative Folgen für die Umwelt haben.
83		Ich finde die Risiken einer CO_2- Speicherstättekontrollierbar.
84	*Risiken CCU-Produktion*	Ich finde den Produktionsprozess ungefährlich.
85		Der Produktionsprozess könnte negative Folgen für die menschliche Gesundheit haben.
86		Der Produktionsprozess könnte negative Folgen für die Umwelt haben.
87		Ich finde die Risiken durch den Produktionsprozess kontrollierbar.
88	*Risiken CCU-Produkt*	Ich finde Produkte aus CO_2 ungefährlich.
89		Produkte aus CO_2 könnten negative Folgen für die menschliche Gesundheit haben.
90		CO_2 könnte an der Oberfläche des Produkts austreten.
91		Ich finde die Risiken durch CO_2-Produkte kontrollierbar.
92	*Risiken CCU-Produktentsorgung*	Ich finde die Entsorgung von CO_2-Produkten ungefährlich.
93		Die Entsorgung von CO_2-Produkten könnte negative Folgen für die menschliche Gesundheit haben.
94		Die Entsorgung von CO_2-Produkten könnte negative Folgen für die Umwelt haben.
95		CO2 könnte bei der Entsorgung der Produkte entweichen.
96	*CCU-Akzeptanz*	Ich denke, CCU ist nützlich.
97	*(min =1, max = 10)*	Ich denke, CCU ist vorteilhaft.
98		Ich denke, CCU ist akzeptabel.
99		Ich denke, CCU ist frei von Risiken.
100		* Ich denke, CCU ist umweltfreundlich.

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